A census of Tehuantepec and Papagayo eddies in the northeastern tropical Pacific

Daniel M. Palacios[1,2] and Steven J. Bograd[2]

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[1] We use a 12-year (1992–2004) time series of satellite altimetry to characterize long-lived, wind-generated anticyclonic eddies originating in the Gulfs of Tehuantepec and Papagayo in the northeastern tropical Pacific. A total of 42 Tehuantepec and 26 Papagayo eddies were observed. Eddy merging, usually of a Tehuantepec-Papagayo pair, was observed on 16 occasions. On average, the eddy season began in late October and lasted approximately 250 days until early July, with 3.5 Tehuantepec and 2.2 Papagayo eddies formed each year. Minimum average eddy lifespan was 143 days and 84 days for Tehuantepec and Papagayo eddies, respectively. There was considerable interannual variability in eddy activity, with greater (fewer) number of eddies, more intense (weaker) eddies, and a longer (shorter) eddy season during El Niño (La Niña) years. Eddy intensification was consistently observed at the East Pacific Rise. **Citation:** Palacios, D. M., and S. J. Bograd (2005), A census of Tehuantepec and Papagayo eddies in the northeastern tropical Pacific, *Geophys. Res. Lett.*, *32*, L23606, doi:10.1029/2005GL024324.

1. Introduction

[2] Winter-time cold-air surges over the Gulf of Mexico, as well as intensified NE trades over the Caribbean, form strong wind jets that blow through mountain gaps of southern Mexico and Central America into the Pacific Ocean [*Schultz et al.*, 1998; *Chelton et al.*, 2000]. These strong outflow events force a rapid oceanic response in the Gulfs of Tehuantepec, Papagayo, and Panamá, leading to the development of anticyclonic and cyclonic eddies [*McCreary et al.*, 1989; *Barton et al.*, 1993; *Trasviña et al.*, 1995]. Cyclonic eddies are less numerous and dissipate relatively quickly [*Gonzalez-Silvera et al.*, 2004]. The anticyclonic eddies, on the other hand, have been observed to last up to six months and propagate up to 1500 km offshore [*Hansen and Maul*, 1991; *Müller-Karger and Fuentes-Yaco*, 2000]. These Tehuantepec and Papagayo eddies can be important transporters of biogenic material from the continental margin to the interior northeastern tropical Pacific [*Müller-Karger and Fuentes-Yaco*, 2000; *Gonzalez-Silvera et al.*, 2004].

[3] Tehuantepec and Papagayo eddies were first discovered in infrared satellite imagery, where they were seen as large features (~100–500 km diameter) with strong sea-surface temperature anomalies [*Stumpf and Legeckis*, 1977]. More recent studies have shown they also have distinctive signatures in ocean color (up to 10 mg m^{-3} chlorophyll *a*) [*Müller-Karger and Fuentes-Yaco*, 2000; *Gonzalez-Silvera et al.*, 2004] and sea-surface height (~20 cm) [*Willett*, 1996]. The longevity and propagation characteristics of these eddies have also been measured with satellite-tracked surface drifters [*Hansen and Maul*, 1991; *Willett*, 1996], but directed in-situ sampling of these features has been more limited [*Barton et al.*, 1993; *Trasviña et al.*, 1995, 2003].

[4] We use a 12-year time series of satellite altimetry to conduct a long-term, continuous census of eddy activity in the northeastern tropical Pacific. We quantify the number, intensity, longevity, and propagation characteristics of Tehuantepec and Papagayo eddies over this period. Satellite altimeters are particularly well suited for such a census because they are not hindered by clouds and because eddies maintain a discernable height signature until dissipation [*Willett*, 1996]. Our results have implications for improved regional modeling and a better understanding of the biological impacts of these eddies as they propagate offshore.

2. Data and Methods

2.1. Data Sources

[5] Digital bathymetry for the description of topographic features in the northeastern tropical Pacific (Figure 1) was

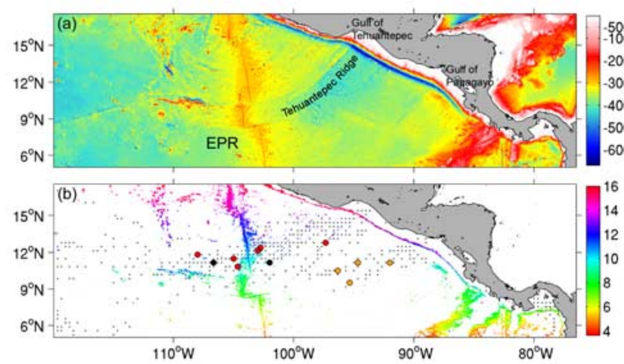

Figure 1. (a) Map of region with bathymetry (in m) showing the location of the East Pacific Rise (EPR), the Tehuantepec Ridge, and the Gulfs of Tehuantepec and Papagayo; (b) Map of *f*/*H* for all depths between 2000–3000 m (in 10^{-8} m^{-1} s^{-1}) (range is restricted because *f*/*H* varies over four orders of magnitude in this region). The locations of peak positive anomaly of SLA for each 7-day map for the period 14 October 1992–18 August 2004 are shown as gray dots. The locations of peak positive anomaly of SLA observed each season are shown as filled circles, color-coded by eddy type (T = red, P = orange, M = black).

[1]Joint Institute for Marine and Atmospheric Research, University of Hawaii, Honolulu, Hawaii, USA.
[2]NOAA, Southwest Fisheries Science Center, Environmental Research Division, Pacific Grove, California, USA.

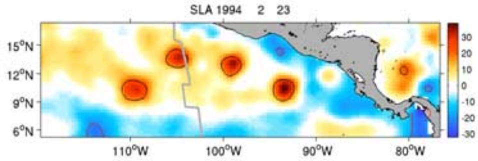

Figure 2. Snapshot of animated sequence of 619 maps of SLA for the northeastern tropical Pacific region at 7-day intervals, spanning the period 14 October 1992–18 August 2004. The animation is available in the HTML version.

extracted from the global sea floor topography of *Smith and Sandwell* [1997]. This product has a resolution of 2 arc minutes (~4 km), and is available from the Institute of Geophysics and Planetary Physics at the Scripps Institution of Oceanography (http://topex.ucsd.edu/). Sea level anomalies (SLA) were extracted from the 7-day, 1/3-degree resolution merged altimetry product [see *Ducet et al.*, 2000], distributed by the Aviso project (http://www.aviso.oceanobs.com/) for the period 14 October 1992–18 August 2004.

2.2. Eddy Identification

[6] We used 619 7-day maps of SLA for the period 14 October 1992 – 18 August 2004 in this study. A contour value of +20 cm (−20 cm) was selected by trial and error as a threshold that consistently identified persistent anticyclonic (cyclonic) eddies in the region. Eddies were counted from the time they first reached these values if they persisted for at least four consecutive 7-day periods. Most cyclonic eddies did not meet this criterion and therefore this paper deals only with anticyclonic eddies. Each anticyclonic eddy was tracked through time until SLA dropped below the +20 cm threshold value, at which time it was considered as dissipated. The exception was when an eddy temporarily weakened and then reappeared, in which case the weakened eddy was visually tracked and counted as such as long as it maintained a coherent structure and returned to the threshold value. Because of the criteria used for eddy identification, the longevity and number of eddies in this study should be considered a minimum. Numerous weaker and shorter-lived eddies were observed in the region but were not counted in this census. Animation 1 shows a sequence of the 619 SLA maps (see also Figure 2).

3. Eddy Census

[7] Interannual variability in the number, size, and intensity of Tehuantepec and Papagayo eddies is evident from maps of SLA at the times of peak eddy activity for each eddy season (Figure 3). Eddies of high SLA extend westward from the coast within a latitudinal band between 8°N – 15°N, with dimensions ranging from ~100 km to over 400 km diameter. Particularly large and intense eddies (peak SLA over +40 cm) were evident during the 1997–1998 and 2002–2003 El Niño winters. These eddies maintained their strength for several months as they propagated westward beyond the East Pacific Rise (EPR, Figure 1a) within a background of anomalously high sea level. By contrast, winters following an El Niño event (e.g., 1995–1996, 1998–1999, and 2003–2004) were characterized by smaller, less intense eddies within a background of generally low sea level.

[8] The total number of observed eddies varied considerably from year to year, with as few as three (1995–1996) and as many as 13 (1997–1998; Table 1 and Figure 4). There were more Tehuantepec than Papagayo eddies formed each year, with the exception of 1998–1999 and 1999–2000, when equal numbers were observed (Table 1). On average, 3.5 Tehuantepec and 2.2 Papagayo eddies were observed each winter, similar to that found by *Willett* [1996]. Tehuantepec eddies tended to be more intense and longer-lived than Papagayo eddies (minimum average lifetimes of 143 days and 84 days, respectively), although they are typically of similar size. Papagayo eddies always dissipated (or merged) before crossing the EPR, while Tehuantepec eddies were often tracked to the edge of the study region at 120°W.

[9] There is also significant interannual variability in the timing and duration of the eddy season (Table 1 and Figure 4).

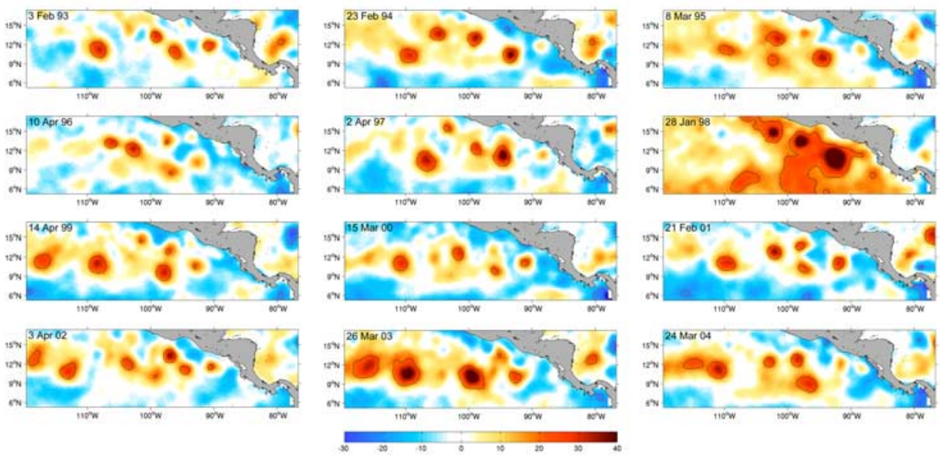

Figure 3. Maps of SLA (in cm) for the 7-day period of peak eddy activity during each eddy season, over the period 14 October 1992 to 18 August 2004. The +20 cm contour is marked in black. Range is restricted for display purposes; values as low as −37 cm and as high as +59 cm occur at the strongest features. Dates of each image are marked in upper left of each panel.

Table 1. Census of All Tehuantepec (T), Papagayo (P), and Merged (M) Eddies Observed in 619 SLA Maps Over the Period 14 October 1992 to 18 August 2004[a]

Season	Start date	End date	Duration	SLA_{max}	T	P	M
1992–1993	14 Oct	15 Sep	337	39.6 (M)	4	3	1
1993–1994	24 Nov	20 Jul	238	41.9 (T)	3	2	0
1994–1995	7 Sep	28 Jun	294	35.2 (P)	3	1	2
1995–1996	13 Dec	22 May	161	33.2 (T)	2	1	0
1996–1997	20 Nov	18 Jun	210	42.1 (P)	4	1	2
1997–1998	30 Jul	23 Sep	420	59.3 (P)	6	4	3
1998–1999	2 Dec	26 May	175	40.8 (T)	3	3	0
1999–2000	1 Dec	14 Jun	196	35.3 (P)	2	2	1
2000–2001	25 Oct	27 Jun	245	39.6 (M)	5	3	3
2001–2002	31 Oct	19 Jun	231	37.8 (T)	3	3	2
2002–2003	4 Sep	28 May	266	49.7 (T)	4	1	1
2003–2004	19 Nov	23 Jun	217	39.4 (T)	3	2	1
Mean	~26 Oct	~2 Jul	249.2	41.2	3.5 (142.9)	2.2 (83.5)	1.3 (73.7)

[a]Duration is number of days between start and end date of eddy season. SLA_{max} (cm) is the peak positive anomaly observed each season, with type of eddy containing that value in parentheses. Numbers in parentheses next to mean eddy counts are the mean lifetime, in days, of each eddy type. The start of the 1992 eddy season may have occurred prior to the first SLA map on 14 October. Mean Tehuantepec eddy longevity is likely an underestimate, since several eddies were still coherent as they reached the western edge of the study region.

On average, the eddy season begins in late October and ends in early July, extending for nearly 250 days. But the full range of the eddy season varied from 161 (1995–1996) to 420 days (1997–1998), with a starting date observed as early as 30 July (1997) and as late as 13 December (1995). End dates ranged from May through September. The strong El Niño of 1997–1998 resulted in the earliest and longest eddy season, along with the greatest number of eddies (Table 1 and Figure 4) and strongest eddy intensity (Table 1 and Figure 3). La Niña years (1995–1996, 1998–1999, 1999–2000) were characterized by weaker eddy activity and shorter eddy seasons. Regardless of the start and end dates, peak eddy activity was usually observed from late January through early April (Figure 3). In each year, the first observed eddy originated in the Gulf of Tehuantepec. The first Papagayo eddy of the season always formed after 1 January (Figure 4).

[10] On 16 occasions, two eddies were observed to merge into a single coherent feature that was subsequently tracked (Table 1 and Figure 4). The majority (81%) of these mergers involved a Tehuantepec-Papagayo pair, although the merger of two Tehuantepec eddies was also observed. Three mergers were observed in the energetic El Niño year of 1997–1998, while no mergers were observed during the more quiescent strong La Niña years (1995–1996, 1998–1999). A sequence of SLA maps over six weeks in early 1993 shows the evolution of a typical Tehuantepec-Papagayo merger (Figure 5). The two eddies were of similar size and intensity prior to 10 February and drew closer to each other over the next two weeks. By 3 March, the +20 cm contour had enclosed the eddy pair and the Tehuantepec center had intensified. By 17 March, a single eddy, larger

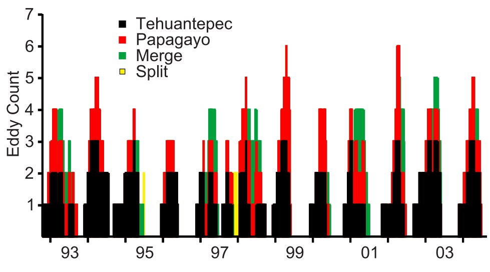

Figure 4. Frequency histogram of number of Tehuantepec, Papagayo, Merged, and Split eddies over the period 14 October 1992 to 18 August 2004. Note that values are stacked by eddy type.

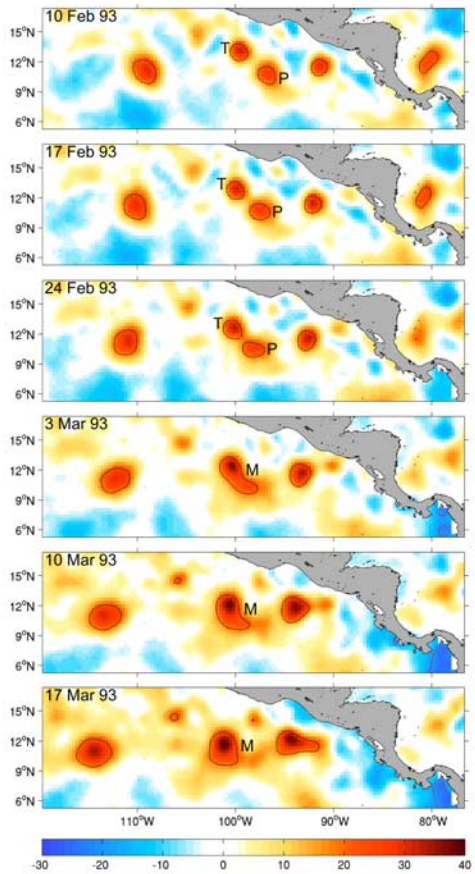

Figure 5. Sequence of SLA (in cm) maps showing a merger between a Tehuantepec and a Papagayo eddy (marked T and P). The +20 cm contour is marked in black. Dates of each image are marked in upper left of each panel.

and of greater intensity than either of the original eddies, was apparent. This merged eddy was subsequently tracked for another 19 weeks to 118°W, where it dissipated. On two occasions west of the EPR, a merged eddy was observed to split into a new anticyclonic pair, although these eddies dissipated within a couple of weeks of the split (Figure 4).

[11] As eddies propagate westward, they encounter the EPR, a fast-spreading mid-ocean ridge system whose axis is oriented at ~346° between 102.4°W–105.4°W (Figure 1a). The sea floor rises from average depths greater than 4000 m along the Tehuantepec Ridge to shallower than 2800 m at the EPR axis. This topography yields a local maximum in f/H (Figure 1b), which, through conservation of potential vorticity [*Pond and Pickard*, 1995], decreases relative vorticity by ~45% (at constant f) and appears to impact the intensity and propagation of the eddies. Of the 22 Tehuantepec and merged eddies that could be tracked coherently to and beyond the EPR, the majority (82%) were observed to intensify and change propagation characteristics in the vicinity of the ridge. The preferred paths of Tehuantepec and Papagayo eddies are clear from the locations of the regional maximum SLA for each 7-day period over the study period (Figure 1b). The trajectories of Tehuantepec eddies are typically southwestward along the Tehuantepec Ridge, probably due to internal dynamics [*Trasviña et al.*, 2003], but become more westward as they cross the EPR in a narrow latitudinal band (10.5°N–13°N). The annual maximum SLA is associated with Tehuantepec eddies or Tehuantepec-Papagayo mergers in seven of 12 years (Table 1), and usually occurs at or just west of the EPR, indicating local intensification (Figure 1b). The typical pathway of Papagayo eddies also tends to be southwestward, although they quickly reach maximum intensity and dissipate well east of the EPR (Figure 1b).

4. Discussion and Conclusion

[12] Long-lived, anticyclonic eddies generated each year along the Central American coast are an important component of the dynamics of the northeastern tropical Pacific. These are intense and stable features lasting up to six months and traveling over 2000 km away from the continental margin. There is significant interannual variability in the number and characteristics of Tehuantepec and Papagayo eddies, and in the timing and duration of the eddy season, associated with the El Niño-La Niña cycle. Enhanced eddy activity during El Niño years is probably linked to the anomalously large number of strong wintertime cold surges into Mexico and Central America [*Schultz et al.*, 1998]. Interannual variability in the regional background sea level and the passage of strong coastally trapped Kelvin waves associated with El Niño may also modulate eddy activity. Amplification of Tehuantepec eddies at the EPR likely extends their longevity.

[13] The annual recurrence, intensity, and persistence of Tehuantepec and Papagayo anticyclonic eddies suggests that they may be important biological hot spots. Like Haida eddies in the Gulf of Alaska [*Miller et al.*, 2005], they transport nutrient-rich coastal waters and organisms to the ocean interior. Ecological evolution within their core is implied by the transition from downwelling processes during intensification to upwelling as they decay [*Flierl and McGillicuddy*, 2002]. Also, their peripheries are dynamic frontal areas of enhanced physical-biological interactions that attract top-level predators [*Griffin*, 1999; *Olson*, 2002]. Further observations and modeling are needed to better understand the dynamics and biological relevance of these eddies.

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S. J. Bograd and D. M. Palacios, NOAA, Southwest Fisheries Science Center, Environmental Research Division, 1352 Lighthouse Avenue, Pacific Grove, CA 93950-2097, USA. (daniel.palacios@noaa.gov)